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SURVEY OF MEASUREMENTS OF THE FISSION NEUTRON SPECTRUM OF ^{252}Cf

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1. INTRODUCTION

An accurate knowledge of the shape of the neutron spectrum is of primary interest in reactor physics calculations. This is true for the fission spectra of isotopes other than the extensively investigated ^{235}U. Such data can also lend insight by comparisons with similar measurements on ^{235}U. Most of the measured neutron spectra are described very well by the Maxwellian distribution. Experimental neutron spectrum data on ^{252}Cf spontaneous fission are compiled in Table I and are displayed Fig. 1, which gives the Maxwellian temperature (T) as a characteristic parameter of the spectral shape. When studying the table one is struck by the observation that in spite of the relatively small errors quoted there are rather large divergences between the values. This indicates large systematic uncertainties.

From the theoretical point of view, Terrel's relation [21] between T and $\bar{\nu}$ /average number of neutrons from fission/ represents a guide for an expected trend. However, it gives a large scattering between data points and at best one can only say that the T-$\bar{\nu}$ relation demonstrates some degree of trend. It is clear, therefore, that there is a need for new accurate measurements and for a serious evaluation of all important sources of error.

The increasing availability of ^{252}Cf has made it a convenient neutron source and thus it is very desirable to have an accurate knowledge of its neutron energy distribution. We have attempted in this paper to explain the large spread in the ^{252}Cf fission neutron spectrum data and to estimate the best value of T from a detailed analysis of the experimental circumstances and the necessary corrections.

2. BACKGROUND CORRECTIONS IN TOF MEASUREMENTS

Most of the measurements referred to were carried out using time-of-flight (TOF) techniques. Before dealing with the measurements we shall discuss the possible sources of background and the corrections that they entail in TOF measurements on fission neutron spectra in general. The discussion is applicable to experiments where:

a/ the start signal to the time-to-pulse height converter is provided by a neutron detector sensitive to both neutrons and gamma rays;

b/ the stop signal is provided by a fission detector sensitive to fission fragments only. The fission detector records all the fission events, so that the total neutron spectrum averaged over all angles can be measured.

A. Random background.

The random coincidence background can be measured simultaneously in a given range of the spectrum by suppressing systematic events in this region with appropriate delays. The distribution of background caused by the random coincidences is flat.

A special type of random coincidences, the "systematic-random" coincidences, emerges in the fission neutron spectrum measurements, but these are not measurable directly. The number of accidental coincidences is given by $N = 2\tau N_n N_f$, where τ is the time resolution of the coincidence unit and N_n and N_f are the count rates of the neutron and fission detector, respectively. It is necessary to calculate N for each channel of the multichannel analyser because N_n varies from channel to channel. N_n is the number of events preceeding an event in the i-th channel. The number of systematic-random coincidences in the i-th channel is given by

$$N^i = \sum_{i=j+1} N_n^j \cdot \tau \cdot N_f$$

where τ is the channel width in time units, N_f the fission rate per unit time and N_n^j the number of events in the j-th channel. The factor of 2 disappears, because the events cannot occur in the reverse time direction.

This type of background depends on the shape of the measured spectrum. In general, the distribution of the systematic-random coincidences is nearly flat, slightly decreasing with increasing channel number. If this type of background is neglected the value obtained for T willbelow, because the systematic-random background is important only in the low-energy part of the spectrum.

B. Scattered background.

The relative number of scattered neutrons that are detected depends strongly on the experimental circumstances. It can be measured by placing a shadow cone between the source and the neutron detector to shield against direct neutrons.

The detection of scattered neutrons in coincidence with fission fragments will decrease the value of the average neutron energy, and hence the value of T will also be lowered. / Assuming Maxwellian distribution, the average neutron energy / $\bar{E}$ / is $\frac{3}{2}$ T./

C. Delayed gamma rays

The existence of delayed gamma rays in the ^{252}Cf fission process was pointed out first by Johansson [10] . It was later shown that the detection of delayed gamma rays could strongly distort the low--energy part of the neutron spectrum [6] . The background caused by these delayed gamma rays can be measured at short flight paths. If the spectrum distortion caused by the detection of delayed gamma rays is neglected T will again be too low.

No correction was made for delayed gamma rays in data published before Johansson's work. We have estimated the magnitude of the delayed gamma rays using the recent data of John et al. [11] , who measured the energy, half-life and intensity of 144 gamma rays and the mass of the emitting fragments. For $0.2 < E < 2$ MeV and $t < 100$nsec, the total gamma ray energy of unresolved lines is at most 20 % of that of resolved lines, so that our calculations can give a lower limit for the magnitude of the delayed gamma rays.

3. METHOD OF EVALUATION OF NEUTRON AND GAMMA RAY DISTRIBUTIONS

We calculated the efficiency of detection of neutrons and gamma rays, the energy distribution of the fission neutrons and the time distribution of delayed gamma rays. Two different types of scintillator were used to detect the neutrons: organic plastics and ^{6}Li-loaded glass scintillators. Since very few data were available on the detection of low-energy neutrons and gamma rays by organic plastic scintillators, the calculations were carried out as for anthracene scintillators, which have a similar chemical structure and density. It has been shown that the relative light output for the detection of different charged particles is the same both for anthracene and organic plastic scintillators [14] .

The efficiency of neutron detection was calculated by the following formula:

$$\varepsilon_n(E) = \left(1 - e^{-\mu_H \cdot \ell}\right) \cdot \frac{E - E^n_{th}}{E}$$

where μ_H is the macroscopic cross-section of (n,p) scattering, ℓ is the thickness of the scintillator and E_{th}^{n} is the energy threshold for neutron detection. The validity of this simple formula has already been proved experimentally [16] . μ_H for anthracene was calculated from the appropriate tables [19] . The value of E_{th}^{n} was determined for each measurement.

The efficiency of detection of the gamma rays was calculated from data on the gamma-ray absorption coefficients of anthracene [15] In the investigated energy range Compton scattering is the only possible absorption process and therefore the effect of the detector threshold on the efficiency curve was accounted for in the same way as in neutron detection:

$$\varepsilon_{\gamma}(E) = \varepsilon_{o} \cdot \frac{E - E_{th}^{\gamma}}{E}$$

The value of E_{th}^{γ} was determined for each measurement.

In the case of ^{6}Li glass scintillators an absolute neutron efficiency curve was used [6] . The threshold for gamma-ray detection is about 0.8 MeV. We measured the efficiency of Li-glass scintillator for the detection of ^{60}Co and ^{22}Na gamma rays and found it was 1.2 %, compared with 1 % efficiency reported for ^{60}Co gamma rays [6] . Above 0.8 MeV delayed gamma rays are in the energy range of 1.2-1.3 MeV only [11] and thus the measured efficiency values could be taken into account.

The neutron energy distribution was assumed to be Maxwellian, with an energy parameter of T=1.5 MeV ; it was normalized to give $\bar{\nu}$ = 3.77 neutrons per fission. Taking into account the efficiency curve and the flight path, the energy distribution was transformed into a time distribution.

The time distribution of delayed gamma rays was calculated from published data [11] . The distribution of each gamma ray was normalized to give the measured intensity per fission. The "measured" distribution of delayed gamma rays was given by taking into account the efficiency and summing up all the gamma rays.

By comparing the calculated distributions of the neutrons and delayed gamma rays we can deduce the magnitude of the distortion effect caused by the detection of delayed gamma rays in ^{252}Cf fission neutron spectrum measurements.

4. DISCUSSION OF TOF MEASUREMENTS

The most important data on TOF measurements are listed in Table II. The background estimations were made from these figures.

A/ Smith et al. [2] did not report any data on the threshold energy of neutron detector. Assuming different threshold energy values for neutron detection we calculated the measured neutron spectrum by the method outlined above. The best agreement between the calculated and the measured neutron spectrum was achieved with a value of E^n_{th} = 100 keV. The 100 keV threshold energy for neutrons corresponds to a 5 keV threshold energy for gamma rays. / The light output of anthracene for 100 keV energy protons is equal to the light output of 5 keV energy electrons [17, 18] . Gamma radiation with an energy of 5 keV lose its total energy in the scintillator [18] ./ The calculated neutron and delayed gamma ray distributions can be seen in Fig.2. The background due to the delayed gamma rays is rather important. The number of detected delayed gamma rays relative to the number of detected neutrons is 10 % at 0.2 MeV neutron energy, 3.6 % at 0.5 MeV and 1 % at 2 MeV. Taking into account this correction, we got a 5-10 % higher value than the single measured value for the temperature of the Maxwellian distribution.

The effect of systematic-random coincidences was not considered, although this type of background also can decrease the T value.

B/ Bowman et al. [4] measured the angular distribution of neutrons. The value of T was calculated from the integrated angular distribution. The scattered background was measured and the systematic-random background was calculated, but these components were disregarded in the data analysis. The authors determined the background in different parts of the spectrum: in the random coincidence region, in the valley between the neutron and prompt gamma-ray peaks; and below 450 keV neutron energy, where the detector efficiency was 0 for neutron detection. The background distribution was calculated from these values for the whole spectrum, and thus the real value of background was determined without any knowledge of the existence of delayed gamma rays.

C/ The results of our calculations for the measurements of Condé et al. [5] with a Li-glass scintillator can be seen in Fig.3. Above 200 keV the number of detected gamma rays is negligible. In measurements with a plastic scintillator the threshold energy of neutron detector was 5 keV for gamma rays [9] , which corresponds to 100 keV for neutrons, as noted in the discussion of Smith's measurements. The calculated distributions are plotted in Fig.4.The relative number of detected delayed gamma rays is 5 % at 0.3 MeV and 2 % at 1 MeV. The distortion of the spectrum is not negligible.

There was no measurement of scattered background and the contribution of systematic-random background was not calculated. Since all neglected background sources decrease the T value, the measured value of T=1.39 MeV is too low.

D/ Meadows [6] analysed and determined all types of background.

His measurements show a small deviation from the Maxwellian shape below 0.5 MeV and gave a result of T=1.565 MeV calculating between 0.003 and 15 MeV, and T=1.592 between 0.5 and 10 MeV.

E/ Zamyatnin et al. [7] took all types of background into account except that due to the delayed gamma rays. The detector threshold energy was 59 keV for gamma rays, which is equal to 345 keV for neutro [4] . The calculated distributions can be seen in Fig. 5.The distortion caused by the detection of delayed gamma rays is not negligible, therefore the value of T=1.48 given by the authors is somewhat low.

5. MEASUREMENTS WITH OTHER METHODS

When other methods are used to determine neutron energies the background sources differ somewhat from those in TOF measurements. Important distortion can be caused by the detection of delayed neutrons arising 2-20 sec after fission. In the spontaneous fission of ^{252}Cf 0.86 % of all the neutrons are delayed [13] . Although the average energy of these neutrons is not known, the average energy of 450 keV measured for ^{235}U and ^{239}Pu [20] may be valid for ^{252}Cf too.

A/ Hjalmar et al. [1] measured the neutron spectrum with photoplates by computing the neutron energy from the tracks of recoiled protons in emulsion. Only 281 tracks were recorded, and the low energy part below 2 MeV was not considered. The statistical validity of this measurement is doubtful.

B/ The neutron distribution reported by Smith et al. [2] was measured above 2 MeV with photoplates. The spectrum was evaluated by Condé [5] , who gave a value of T=1.57 MeV.

C/ Bonner [3] measured the neutron spectrum by means of a sphere-moderated neutron spectrometer [8] . Neutrons were detected in a small ^{6}LiI/Eu/ scintillator placed at the centre of polyethylene moderating spheres with sizes ranging from 5.1 to 30 cm in diameter. The counting-rate ratio of spherical counters with different sizes is a sensitive function of neutron energy. Assuming Maxwellian distribution for the fission neutrons the measured ratio will be a function of T only. The best value of T computed from six independent measurements with different detector pairs was T=1.367. Background was measured without the ^{252}Cf source in position but the number of scattered neutrons was not determined, which means that the value of T was lowered.

We calculated the contribution of delayed neutrons for one of the detector pairs / 20 and 7.6 cm spheres / using the efficiency curves given by Bonner. This gives a value of T reduced by 30 keV. The decrease in T value due to delayed neutrons was larger for the other detector pairs. The contribution from the detection of prompt gamma rays is negligible.

6. CONCLUSIONS

The effect of different components of the background on measurements of fission neutron energy spectra of ^{252}Cf have been discussed and it has been pointed out that failure to allow for them results in a neutron spectrum with a lowered temperature parameter. The neglect of all [5] or some [2,7] of the components due to detected gamma rays, systematic-random coincidences and scattered neutrons in time-of-flight measurements has meant that calculations of the Maxwellian temperature are too low by 100-150 keV.

Other measurements obtained using different methods [2,4,6] have precise background corrections and give almost identical values for the neutron spectrum parameter: 1.57±0.05, 1.56, 1.565 and 1.592, respectively.

If the spectrum-distorting effects due to the different backgrounds are properly accounted for, it seems that the most probable value of the Maxwellian temperature is about 1.57 MeV. This gives a value of 2.355 MeV for the average energy of fission neutrons from the spontaneous fission of ^{252}Cf.

Table I.

Results and methods of neutron energy spectrum measurements for ^{252}Cf spontaneous fission

Authors	Method	Maxwellian temperature MeV	Ref.
E.Hjalmar et al.	Photoplate	$1.402^{+0.098}_{-0.085}$	1
A.B.Smith et al.	Photoplate	1.57±0.05	2
	Time-of-flight	1.42±0.05	
T.W.Bonner	"Bramblett" counter	1.367±0.030	3
H.R.Bowman et al.	Time-of-flight	1.56	4
H.Condé et al.	Time-of-flight	1.39±0.04	5
J.W.Meadows	Time-of-flight	1.592, 1.565	6
Y.S.Zamyatnin et al.	Time-of-flight	1.48±0.03	7

Table II.

Characteristic parameters of the experimental arrangements for TOF measurements

Authors	Ref.	E_n MeV	neutron detector	ℓ cm	n det.threshold keV		L cm
					E_n	E	
A.B.Smith et al.	[2]	0.2-3	Pilot B plastic	3.81			80
H.R.Bowman et al.	[4]	0.5-6	Pilot B plastic	5.08	345	59	93
H.Condé et al.	[5,9]	0.07-0.5	Li-glass	0.95		800	25
		0.3-7	NE-102 plastic	5.08		5	100
J.W.Meadows	[6]	0.003-2	NE-905 Li-glass	0.95		800	18.6 32.7 134.2
		1-15	Hydr.liq. scintillator	2.35	850 4000 6500		138.6
Yu.S.Zamyatnin et al.	[7]	0.4-6	plastic	3.0		59	50

E_n - measured energy range of neutrons

ℓ - thickness of the scintillator

E_n , E_γ - threshold energy of the neutron detector for neutron and gamma ray energies, respectively

L - flight path

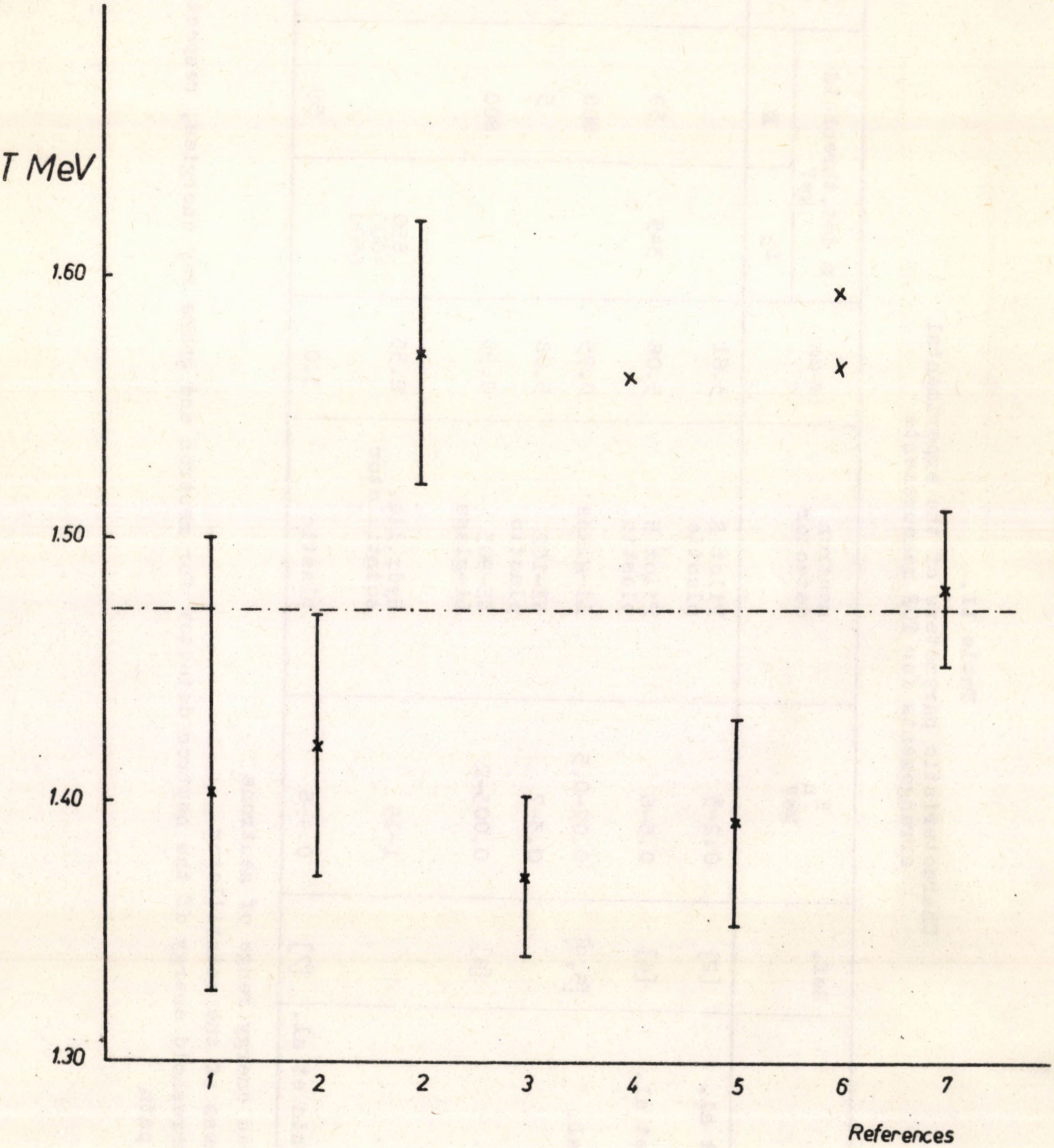

Fig.1

Reported values [1-7] of the Maxwellian temperature T for the energy distribution of neutrons from ^{252}Cf fission

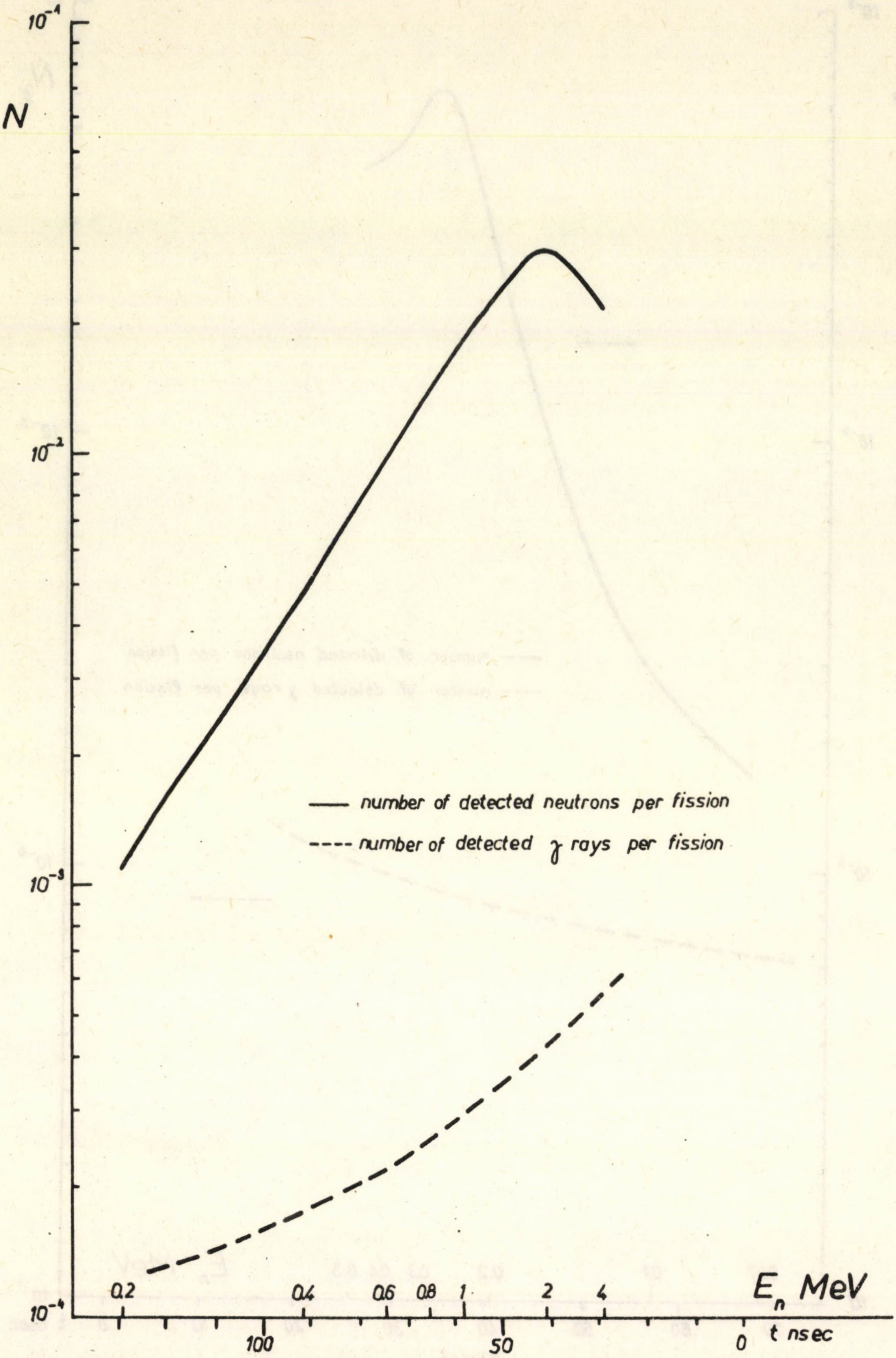

Fig.2

Calculated distributions of neutrons and delayed gamma rays for the measurement of Smith et al. [2]

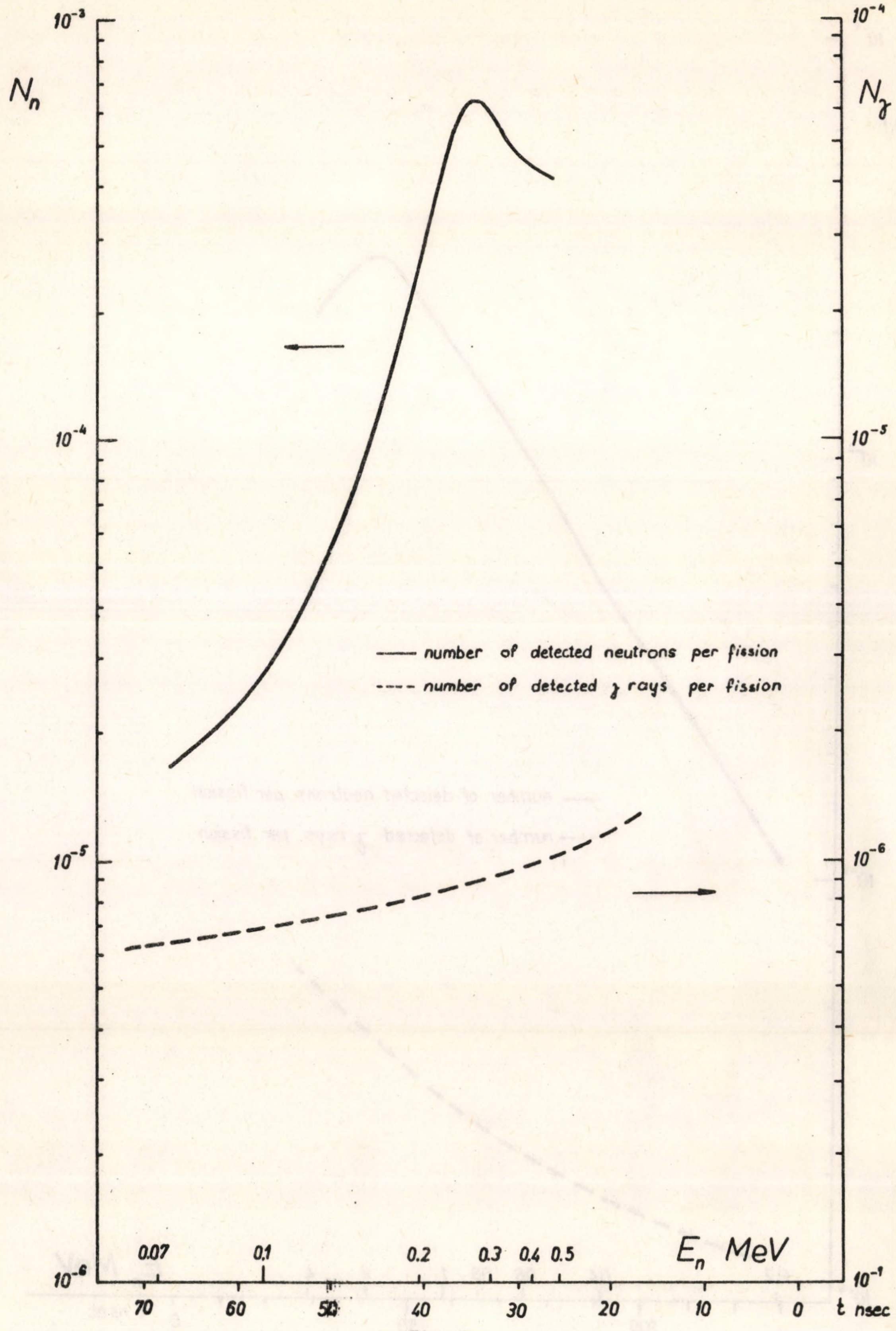

Fig.3

Calculated distributions of neutrons and delayed gamma rays for the measurement of Condé et al. [5] with a Li-glass scintillator

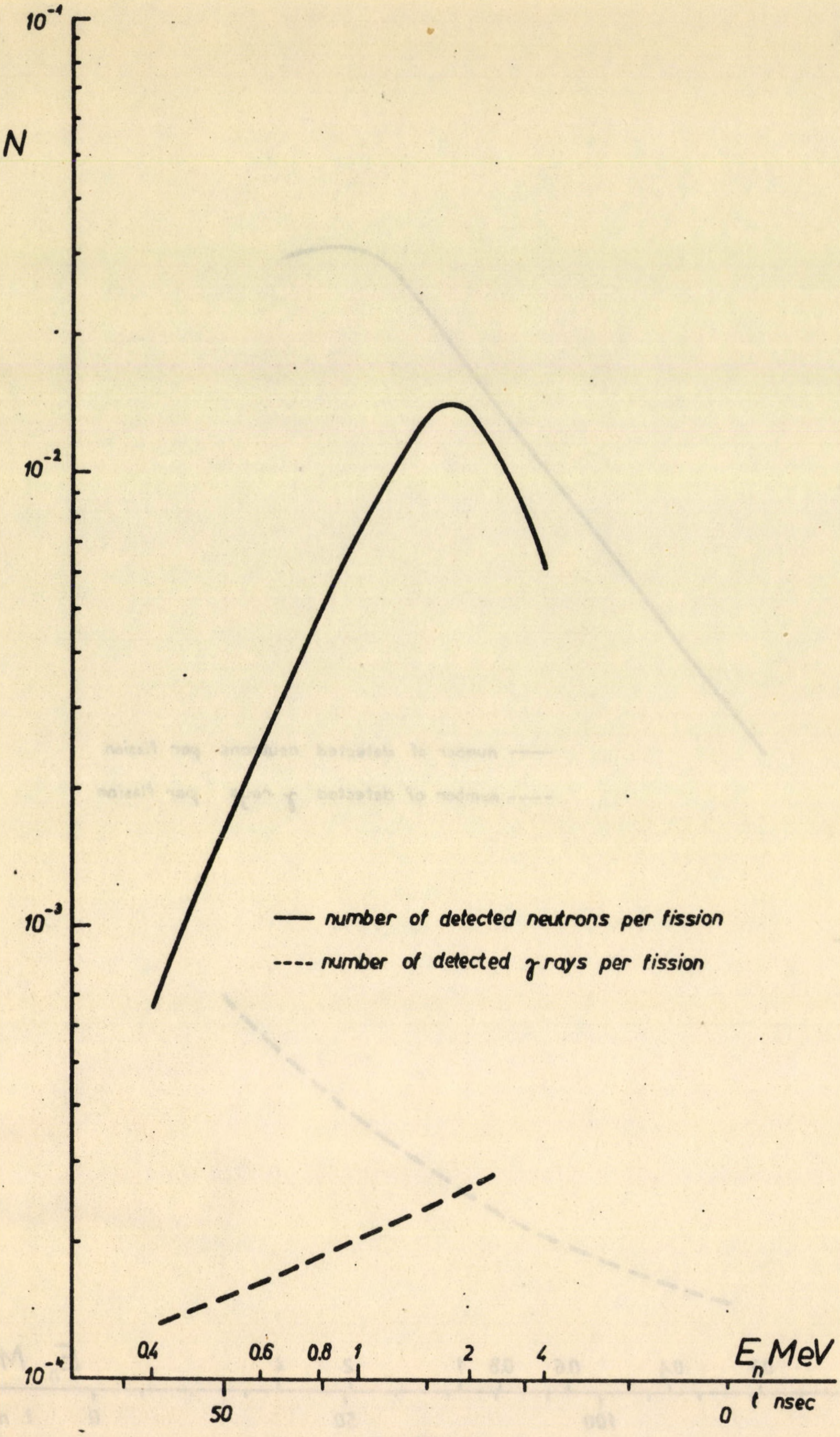

Fig.4

Calculated distributions of neutrons and delayed gamma rays for the measurement of Condé et al. [5] with a plastic scintillator

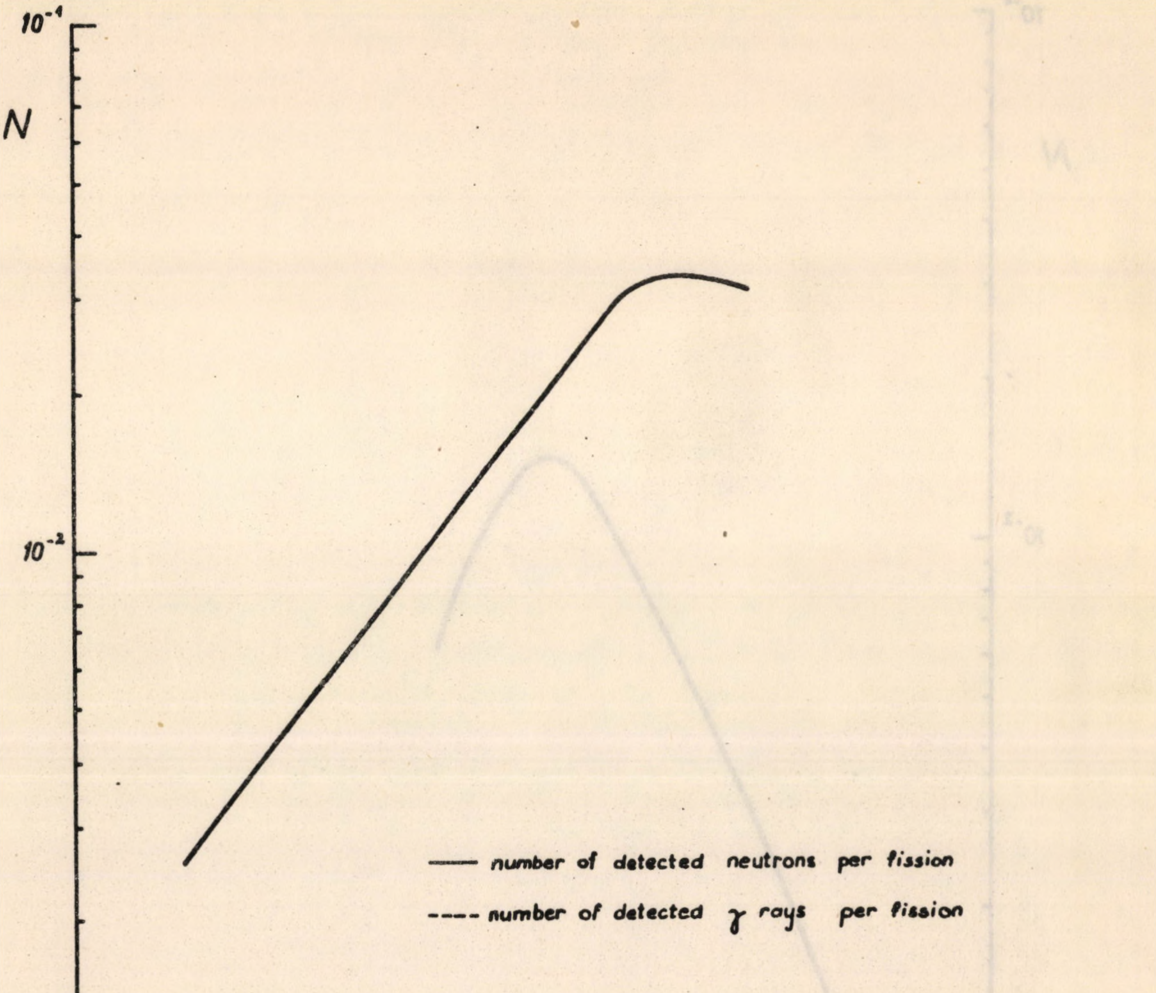

Fig.5

Calculated distributions of neutrons and delayed gamma rays for the measurement of Zamyatnin et al. [7]

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ABSTRACT

The background sources arising in different techniques for measuring fission neutron energies were studied in detail and the background due to the detection of delayed gamma rays was calculated. The proposed value of the Maxwellian temperature for the energy distribution of neutrons from the spontaneous fission of ^{252}Cf is about T=1.57 MeV.

РЕЗЮМЕ

Подробно исследовались источники, возникающие при различных методах измерения энергии нейтронов деления и был вычислен фон, вызванный регистрацией запаздывающего гамма-излучения. Для температуры Максвеля энергетического распределения нейтронов спонтанного деления ^{252}Cf получили значение Т~I.57 мэв.

Kivonat

Különböző módszerekkel történt hasadási neutron energiaspektrum-méréseknél vizsgáltuk a lehetséges háttérforrásokat s kiszámitottuk a késleltetett gammasugárzás detektálásából adódó hátteret. A ^{252}Cf spontán hasadásánál keletkező neutronok energiaeloszlását leiró Maxwell-eloszlás energiaparaméterének legvalószinübb értékeként T = 1.57 MeV adódott.

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